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Minimising Down Hole Mud Losses

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Abstract

The application of particle sealing technology, field monitoring techniques and improved operational practices has been used to minimise downhole lost circulation while drilling extended-reach wells. These techniques have been applied at the Wytch Farm Development in Southern England and in the Pompano Development in the Gulf of Mexico. Using particle sealing technology, losses were reduced from an average 5,000 bbls of low toxicity mineral oil to zero while drilling the 8 ½" section in offset Wytch Farm wells M-07, M-09 and down hole synthetic mud looses were significantly reduced on Pompano A-18. Pressure While Drilling (PWD) data have contributed to the improved understanding of how changes in downhole pressure influence lost circulation.

Introduction

The loss of whole synthetic or low toxicity mineral oil mud is extremely costly to many operations in terms of unit mud costs, lost circulation materials and non-productive time. The rate of mud loss can vary from steady seepage in high permeability formations through to rapid loss to fractures and faults. In either case the total mud lost can amount to several thousand barrels on a single well.

The problem of losses becomes particularly acute for extended-reach wells. This is because of the greater length of formation exposed, the narrow operating window between pore pressure and fracture gradient and the difficulty in spotting LCM pills. Figure 1 illustrates the influence of hole angle on the pore pressure/fracture gradient window[1]. Managing this narrow margin in extended-reach wells is made more difficult by the Equivalent Circulating Density (ECD) which is inherently high for wells with long horizontal departures.

Options for Controlling Losses.

There are a number of factors that can influence the likelihood of a well experiencing lost circulation. These factors relate to both the planning and execution stages of well construction. The design and drilling parameters which are the major drivers for controlling lost circulation are:

Wellbore and Drillstring Geometry. Hole size and annular clearances have a big impact on frictional pressure loss. The sensitivity of ECD on hole size, casing design and drillstring geometry should be determine at the planning stage of an extended reach well. It is also possible to use bi-centred bits to further increase the annular gap and hence reduce ECD.

Mud Rheology and Flow Rate. Mud rheology and flow rate influence ECD. The mud properties and flow rate need to be optimised to provide adequate hole cleaning as well as fulfilling the hydraulic requirements of downhole equipment (e.g. motors, MWD and bit nozzles), while at the same time minimizing ECD.

Mud Weight Selection. The appropriate selection of mud weight is critical for extended-reach wells where wellbore stability issues exist. In practice it is often not possible to reduce ECD by lowering the mud weight because of the increased risk of wellbore collapse.

Sealing Capacity of the Drilling Mud. The physical properties of the mud can influence the tendency to lose circulation. In particular the inclusion of sized bridging material can be used to control losses to high permeability formations and small fractures.

Hole Cleaning Efficiency. Effective cuttings transport is critical for extended-reach wells. Failure to transport cuttings effectively to surface will result in a cuttings accumulation in the annulus. This will further increase the ECD. In addition, cuttings beds which form on the low side of the hole will further restrict the annular gap. This will lead to higher frictional pressure drops in the annulus (and hence higher ECD's).

Casing Design Programme. Where possible it is advisable to select casing seats to minimise the exposure time of potential loss zones. Consideration should also be given to running drilling liners rather than full casing strings back to surface. This can help reduce ECD's, although the benefit must be balanced against the potential downside of poorer hole cleaning in the wider annular gap created above the drilling liner.

Lost Circulation Treatments. As well as treating the mud to reduce its potential for lost circulation, it is possible to pump lost circulation materials (LCM's) in the form of discrete pills. These function either by forming physical bridges or by using increases in fluid viscosity to limit fluid penetration into the formation.

Ideally the optimum solution will result in the complete elimination of downhole mud losses. In practice however, it often becomes a case of actively managing losses. This requires rapid identification and deployment of the appropriate response. The main emphasis of this study focuses on the following four aspects: Particle Sealing Technology; Management of ECD; Field Implementation and Contingency Planning. These issues are discussed in more detail in the following sections of the paper.

Particle Sealing Technology.

It has been well established that the physical properties of the drilling fluid can impact its potential for lost circulation. In particular the inclusion of sized particles has shown to be beneficial for bridging pore throats and fractures to stem losses. The principles behind particle bridging are illustrated in Figure 2.

An in-house study was initiated by BP Sunbury to build on the pioneering work of Abrams[2] to establish the fundamental aspects of particle sealing technology. The work involved testing a range of mud formulations with various particle sealing agents (particulates and fibres). The fluid combinations were evaluated in a standard API sand bed test, a purpose built fracture crack cell and in the Permeability Plugging Apparatus (PPA)[3]. The degree to which the mud provides sealing was quantified by both the spurt loss and the total fluid lost in 30 minutes. The results of the study and the practical implications are summarised below.

Particle Size. For effective sealing of pores and fractures the mud should contain a wide range of particles; the largest blocking particles should be at least as large as the fracture width or the diameter of the largest pore throat. The best size distribution will result from obtaining minimum void spaces in the filter cake.

Particle Shape. Results of laboratory tests indicate that particle shape is not critical for sealing capability. Both elongated fibres and rounded calcium carbonate were shown to be equally effective at plugging pore throats and fractures.

Particle Concentration. The higher the solids concentration, the better the sealing capability. A minimum of 10 ppb of large particles is required to seal fractures, whereas sealing pores requires a minimum of 30 ppb total bridging solids.

Particle Density. Fibres have low density and may be preferred in some applications were there are mud weight restrictions. However it must be recognised that mud weight restrictions become less of an issue if effective sealing of the formation can be achieved.

Mud Weight. In low solids systems particle size distribution is critical whereas in high solids muds almost any distribution is effective (providing sufficient large particles are present).

Continuous Treatment v's LCM Pills. For seepage losses it is more effective to have sealing agents continually present in the mud, rather than to spot LCM pills.

Fracture Characteristics. A few micro-cracks are much easier to seal than an array of pores as there is less open surface area. However highly fractured formations may be just as difficult to seal as a porous zone.

Formation Damage. For reservoir drilling calcium carbonate particles are often preferred as they can be readily removed with an acid wash. Ideally the particle bridging should occur at the pore throat or fracture aperture. This will lessen the potential for solids invasion deep into the formation matrix[4].

Economics. The lower cost of calcium carbonate, logistics and less oil on cuttings retention usually makes its use preferable to fibres.

Managing Equivalent Circulating Density.

Optimising system hydraulics is a key factor for successful drilling of extended-reach wells. The specific challenges presented by extended-reach wells include: narrow mud weight operating window; high parasitic pressure loss in the drillstring; high flow rates required for good hole cleaning; high annular pressure loss and an increased potential for barite sag.

For extended-reach wells there is a clear linkage between hole cleaning and ECD. This is illustrated pictorially in Figure 3. At low flow rates where the hole is not fully cleaned, cuttings will accumulate in the annulus. This will result in an increased ECD due to the additional cuttings loading and the annular flow restriction caused by cuttings beds on the low side of the wellbore. If higher flow rates are employed, the increased frictional pressure drop in the annulus will result in a higher ECD. Both these situations are undesirable in formations susceptible to losses. Ideally the drilling and fluid parameters should be tailored to operate in the range of minimum ECD. This requires an understanding of how mud rheology and flow rate influence cuttings transport in highly deviated wells.

Considerable industry effort has been devoted to understanding the mechanisms of cuttings transport in extended-reach wells. Flow rate, mud rheology and drillpipe rotation are all recognised as significant factors which influence the

process. The influence of mud rheology on the minimum flow rate required to clean the hole is shown in Figure 4. These results are for the 8 ½" horizontal section on Wytch Farm using the model developed by Luo et al[5]. The results show that cuttings transport occurs at the lowest flow rate either with a low YP fluid or a high YP fluid. Muds with intermediate viscosity are less desirable. The influence of mud viscosity can be explained by the change in dominant transport forces from lift (turbulent flow) to drag in laminar flow[5]. These results are consistent with field observations that high angle wells can be cleaned with either "thin" fluids or "thick" fluids.

Figure 5 shows the calculated annular pressure loss for the Wytch Farm horizontal section. These data have been calculated using the parallel plate geometry and the Bingham Plastic rheological model[6]. The pressure drops have been calculated at the flow rate corresponding to the minimum requirement for adequate hole cleaning (from Figure 4). Results show that the annular pressure loss (and hence) ECD will continuously increase as the mud YP is increased. The implication of Figure 5 is that for areas with low fracture gradients, it is preferable to use muds with low YP's to minimise ECD. In practice the YP and the low shear rate viscosity will affect the stability of the mud. Often a compromise will need to be reached to minimise barite sag[7]. In cases where ECD is not a concern it is generally recommended that muds with high YP are selected. As well as providing good hole cleaning at lower flow rates, these properties improve cuttings suspension under static conditions and yield lower overall system pressure losses (by virtue of reduced flow rate requirements).

It is now possible to monitor and manage ECD in real-time thanks to the development of commercially available Pressure While Drilling (PWD) tools[8]. These tools have been used on the recent wells at Wytch Farm and on Pompano.

Field Implementation.

The approach of using particle sealing technology together with optimised hydraulics and ECD monitoring has been used for the 8 ½" reservoir sections on Wytch Farm and Pompano. Successful implementation has required optimisation of the mud properties and bridging particles, together with close monitoring and system maintenance. The key components of the process optimisation are described in the following sections of this paper.

Mud Optimisation. Low toxicity mineral oil based mud was selected for Wytch Farm and synthetic based mud for Pompano. Both mud types provide excellent lubricity for minimising torque and drag. Hydraulics and hole cleaning simulations were run to determine the best combination of mud rheology and flow rates to provide adequate hole cleaning. These properties are listed in Table 1.

Calcium carbonate was selected as the bridging material for both mud systems. The particle size optimisation was achieved by testing various combination of particles in the PPA. Details of the PPA test protocol are given in Appendix 1.

The objective of particle sealing is to seal the formation at the same time as it is drilled. Therefore the best particle combination is selected according to the lowest spurt value. The spurt value is recorded as the total volume which passes through the aloxide disc in the first minute of the PPA test. In each case the tests were performed using aloxide discs which mirrored the range of pore sizes encountered in the field. The pore size distributions were determined from Scanning Electromagnetic Microscope (SEM) images of the core material. Details of the calcium carbonate additions and the pore throat sizes are given in Table 2. In practice only the large particles will need to be added after initial treatment because the smaller ones are present in the mud (e.g. barite) or are generated during the drilling process (drilled solids and ground down large particles).

Wellsite Maintenance of Bridging Particles. Having established the optimum concentration of bridging particles from laboratory tests, it is important to ensure that the appropriate levels of solids are maintained within the circulating system. Maintenance of large bridging particles requires changes to the conventional solids control system. This can be achieved by using coarse shale shaker screens and centrifuges in the barite recovery mode.

Modifications to the solids control system are a lot easier to implement on a land operation such as Wytch Farm compared with offshore installations where space is limited. The Wytch Farm rig was equipped with two full hydraulic drive variable speed centrifuges. These were run in series. The first unit was run at a bowl speed of approximately 1000 rpm with the solids effluent (consisting predominantly of large particles) being returned directly to the active mud system. The second unit was used to process the overflow from the first stage separation. This centrifuge was run at maximum bowl speed, normally 3000 rpm, discarding solids and returning the liquid phase to the mud system. This provided the primary means of mud weight control.

The presence and effectiveness of particles in the system should be monitored by using the PPA as a routine wellsite test method. In addition particle size distribution tests can be helpful in confirming that the required range of bridging solids are present in the mud. Figure 6 shows data taken from Wytch Farm which clearly demonstrates the correlation between particle size and PPA results. The results indicate that the d_{90} correlates better with spurt loss than d_{50}. A decrease in d_{90} invariably resulted in an increase in spurt loss.

The successful application of this technique requires that the mud contains the correct size particles over the duration of the interval. It is important to recognise that merely having the correct particle distribution in the initial mud is of little value. Correct solids control techniques must be employed to economically maintain the coarse element in the system. Even

when appropriate solids control techniques are applied, downhole attrition of the large particles will require that they are continuously replenished. Typically 3-4 sacks per hour (165 - 220 lb) of large particles were added on Wytch Farm wells to retain the necessary concentration of large bridging particles.

Monitoring of ECD. Careful monitoring and control of ECD is recognised as critical for drilling extended-reach wells. The advent of real-time PWD has removed the guess work from estimating downhole annular pressures. As well as providing valuable information on the influence of mud properties and flow rates on ECD, the development of PWD tools has helped refine best drilling practices for extended-reach wells[8]. Examples where the drilling practices have been modified based on PWD data include: avoiding excessive penetration rates; using rotary wiper trips to clean up cuttings beds after prolonged periods of slide drilling and controlling pipe running speeds to avoid excessive swab/surge pressures.

Figure 7 shows data taken from the horizontal 8 ½" section on Wytch Farm (M-09). Data are presented showing the measured ECD's for static and rotating drillpipe over a range of flow rates. These data were taken immediately after drilling out the previous 9 5/8" casing shoe. This ensured that any changes in ECD from pipe rotation were caused solely by hydraulics effects rather than changes in density due to entrained solids. Results in Figure 7 show that drillpipe rotation causes an increase in annular pressure loss, although the effect here is relatively small (0.1 ppg change in ECD corresponds to approximately 30 psi annular pressure loss). The prediction in Figure 7 is based on the Hershel-Bulkley model for modified parallel plate geometry[9]. Agreement over the normal range of field operating flow rates (400-500 gpm) is good.

Figure 8 shows data taken from the 8 ½" section on Pompano (A-15). This section was inclined at 60 degrees. It can be seen that the model predictions consistently underpredict the actual ECD by typically 0.5 - 0.6 ppg. The predictions are based on surface mud properties (rheology and density). Examining the PWD data at zero flow rate revealed that the measured hydrostatic pressure was higher than the pressure based on surface mud weight. The difference is generally in the range 0.1 - 0.5 ppg. Part of this difference can be explained by cuttings accumulation in the annulus. Other possibilities which could contribute to the observed difference in static mud weight are mud compressibility effects or barite sag.

The equivalent downhole mud weights determined from PWD have been used to re-calculate the model predictions of ECD. The results are shown in Figure 9. The revised predictions are in closer agreement with the actual downhole ECD's recorded by the PWD tool. The results demonstrate the need to make additional allowances for the influence of cuttings accumulations on ECD. For vertical wells the impact of cuttings accumulation can be estimated based on the Cuttings Transport Ratio[10]. However for high angle wells no simple method exists and decisions are best based on actual field data.

Contingency Planning.

Drilling extended-reach wells requires that the rig crew are on a continual state of preparedness. It is important that crews are fully briefed and alert to any impending drilling problems such as stuck pipe or mud losses. The ability to respond rapidly to early indications or warning signs is also important to minimise the effects of lost circulation.

As part of the detailed planning process, lost circulation decision trees have been developed to allow the field people to rapidly respond to the first sign of lost circulation. An example of a lost circulation decision tree developed for BP's Wytch Farm operation is given in Figure 10. This decision tree has been developed by capturing the experience and learning that has been gained on the early wells drilled in the region.

Careful monitoring of mud pit levels is used to quantify the extent of any mud losses. Depending upon the rate of loss, the appropriate course of action is then followed. This systematic approach avoids time delays in applying the most appropriate remedy.

Field Results on Wytch Farm and Pompano.

The combination of particle sealing technology and ECD monitoring has been used successfully on BP's field developments in Wytch Farm (UK land) and Pompano (Gulf of Mexico).

Wytch Farm Results. The Wytch Farm development wells are a series of extended-reach wells with horizontal displacements up to 8,000 metres[11]. The reservoir sections are drilled in 8 ½" hole and have horizontal sections in excess of 2,000 metres. At the time of preparing this paper, drilling is well underway on a 10 Km step out well in the Wytch Farm Field[12].

Results showing the recorded downhole mud losses for the Wytch Farm reservoir sections are shown in Figure 11. The first application of particle sealing on Wytch Farm was made on M-07. No downhole losses were experienced during drilling. Previous wells had experienced large losses while drilling the reservoir sections. Drilling the reservoir on M-08 encountered two natural faults which resulted in significant losses (see Figure 11). The particles in the drilling fluid were not sufficiently large to seal these fractures. A low compressive strength magnesium cement pill was successfully used to seal the two big faults and drilling continued without further losses.

M-09 is a similar well to M-05 with a similar step-out of 7,600 metres. No losses were observed in M-09 compared with losses of approximately 8,700 bbls in M-05. Particle sealing technology and ECD monitoring played an important role in the improved performance.

Pompano Results. The Pompano platform wells hold the maximum step out record for extended-reach wells in the Gulf of Mexico. They are completed in 8 ½" reservoir sections at hole inclinations up to 80 degrees. Typical reservoir section lengths are between 1,000 & 2,000 feet.

Results showing the recorded downhole mud losses for the Pompano reservoir sections are shown in Figure 12. Pompano A-18 was the first well drilled using both particle sealing technology and PWD. Minimal downhole losses (50 bbls) were registered while drilling, compared to losses of synthetic based mud up to 1,800 bbls in previous extended-reach wells in the same field. A further design change which reduced the ECD was the running of the 9 5/8" casing as a drilling liner.

Even though minimal downhole losses occurred in the reservoir section of A-18, the overall total losses for the section was similar to previous wells. Surface losses were unacceptably high due to fine screens being retained at the shakers. This emphasises the need to make changes to the solids control system to retain the large sealing particles without compromising the surface handing capacity. Lessons learned will be transferred to future wells.

Conclusions and Lessons Learned

1. Particle sealing technology has been successfully employed to minimise downhole losses for extended-reach drilling.
2. Maintaining the desired particle size distribution of sealing material is critical. This requires continuous addition of the largest particles.
3. Modifications to surface solids control equipment is often required to maintain the required level of large diameter sealing particles.
4. Mud rheology and flow rate need to be optimised to provide adequate hole cleaning whilst maintaining a low ECD.
5. Pressure While Drilling is a very useful tool for field management of ECD.

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Appendix 1 - Bridging Particles Test Procedures

1. Conduct SEM on core samples to determine range of pore throat sizes.
2. Select suitable range of aloxide discs based on tests above.
3. Conduct tests in Permeability Plugging Apparatus (PPA) at the estimated overbalance pressure(typical 1,000/2,000 psi) and estimated down hole static temperature.
4. Record fluid loss from PPA after 1 minute. This value is the spurt loss.
5. Record total fluid volume after 30 minutes. The PPT loss is calculated as : Spurt Loss + (2 * (Total Loss - Spurt Loss))

Table 1: Mud Physical Properties

	Wytch Farm (M-09)	Pompano (A-18)
Mud Weight, ppg	8.4	12.8
PV (cP)	15-20	35-40
YP (lb/100 sq ft)	10-14	12-15
Flow Rate (gpm)	400-450	400-450
ROP (ft/h)	40	100

Table 2: Particle Sealing Concentrations

	Wytch Farm (M-09)	Pompano (A-18)	D10 µ	D50 µ	D90 µ
$CaCO_3$ (50)	5 ppb	-	6.5	45	127
$CaCO_3$ (150)	20 ppb	20 ppb	80	154	279
$CaCO_3$ (250)	5 ppb	5 ppb	165	402	608
Barite	-	12.5 ppg	2.3	16	48
Pore Size (microns)	700-800	400-500			

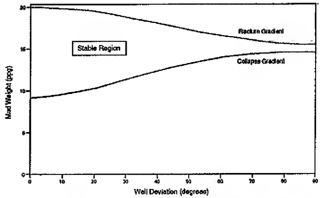

Fig. 1. The influence of well deviation on wellbore stability. Adapted from Ref. 1.

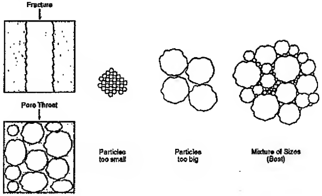

Fig. 2. Pictorial representation of fracture and pore throat sealing using particle sealing technology.

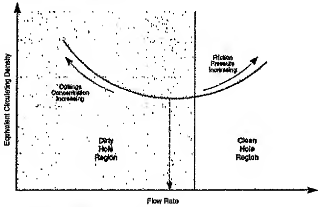

Fig. 3. Effect of flow rate on ECD.

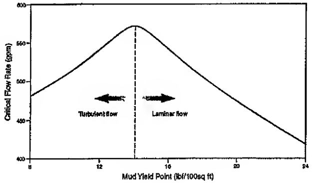

Fig. 4. Influence of mud rheology on hole cleaning.

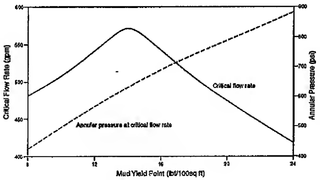

Fig. 5. Influence of mud rheology on annular pressure drop.

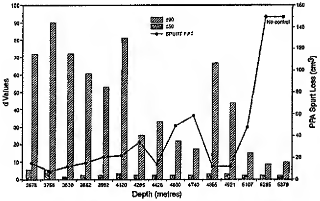

Fig. 6. Correlation between particle size and PPA spurt loss.

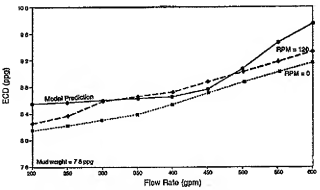

Fig.7. Measurement of equivalent circulating density using PWD.

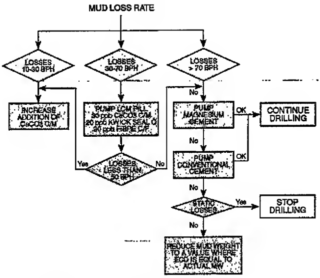

Fig. 10. Losses decision tree for Wytch Farm.

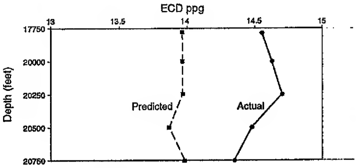

Fig. 8. Predicted vs actual ECD on Pompano A-15 (based on surface mud weight).

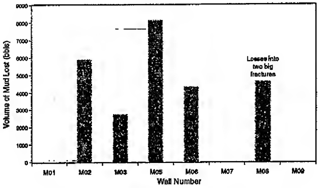

Fig. 11. Downhole mud losses on Wytch Farm 8 1/2" sections.

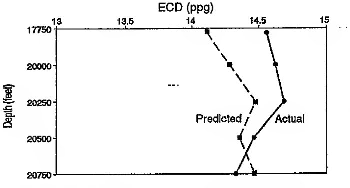

Fig. 9. Predicted vs actual ECD on Pompano A-15 (based on mud weight as measured by the PWD tool).

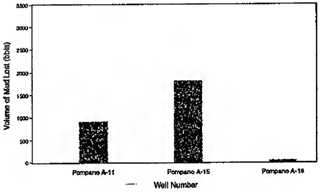

Fig. 12 Downhole mud losses on Pompano 8 1/2" sections.